W/Z+jets measurements at DØ

DIS 2011, Newport News, VA, USA

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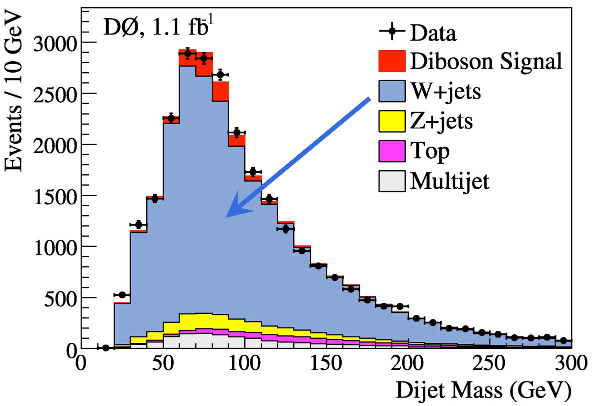
on behalf of the DØ collaboration

Why study W/Z+jets?

Diboson production



Tests of perturbative QCD calculations:

Recent NLO predictions of high jet multiplicities available
Choosing appropriate scale choice not always clear

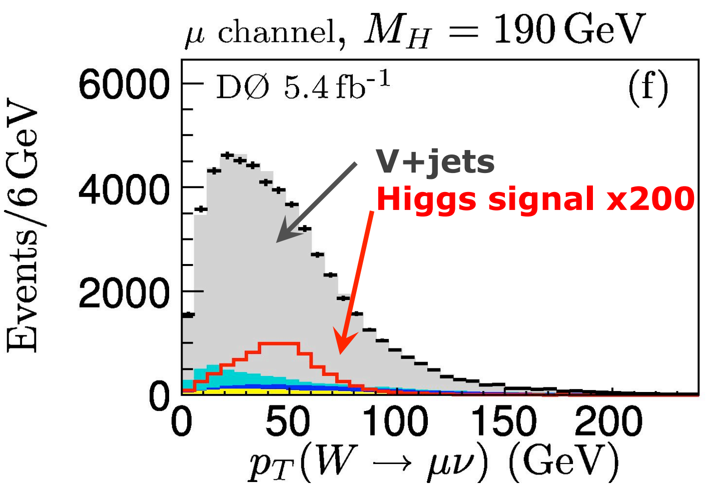
Monte Carlo modelling:

Parton Shower (PS) and PS+Matrix Element approaches need testing/tuning

Experimental measurement:

V+jets dominates many signals of interest: backgrounds to precision measurements of SM processes, and searches for BSM physics

H→WW→lνqq

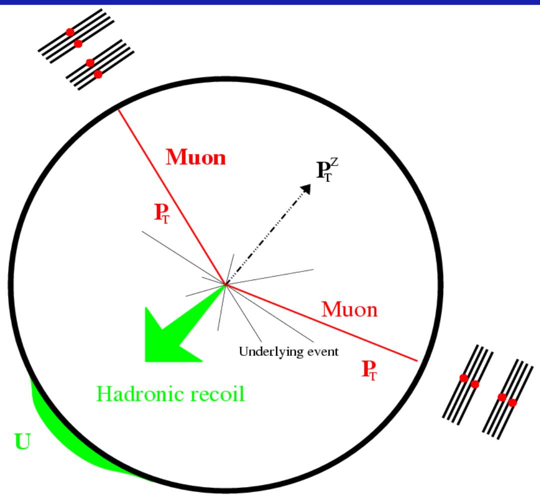


This talk:

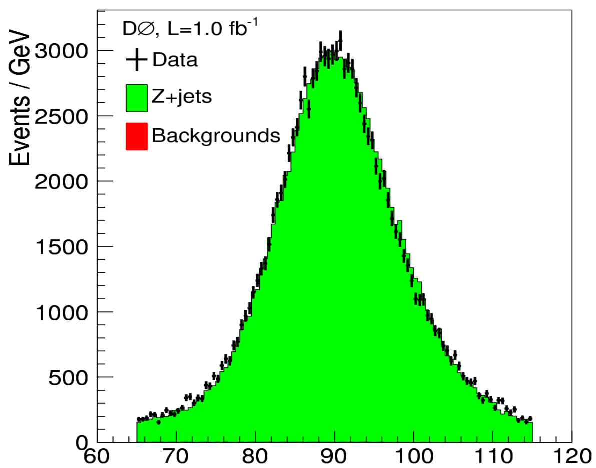
- Z+jet angular correlations
- Z+b/Z+jet inclusive cross-section fraction
- W+(n)jet inclusive cross-section and differential n^{th} jet p_T cross-sections

Z+jets angular observables

Z+jets cross-sections measured as function of angular correlations between leading jet and Z
Provide unique test of pQCD calculations: sensitive to effects not probed in e.g. p_T distributions



$Z \rightarrow \mu\mu$ provides clear, low background signature:
'Physics' backgrounds:
$Z \rightarrow \tau\tau$, WZ, WW, top (0.5–1%)
'Instrumental' backgrounds:
High EM-fraction jets (1%: reject with shower shape cuts)
Semi-leptonic decays (0.5%: reject with isolation criteria)



Correct back to particle-level accounting for detector resolution and efficiencies

Compare to NLO pQCD with MCFM
(apply Pythia-derived UE/hadronization corrections)
Compare to LO ME+PS Alpgen/Sherpa
Compare to LO PS Pythia/Herwig

Z+jets angular observables: $\Delta\phi(Z,j)$

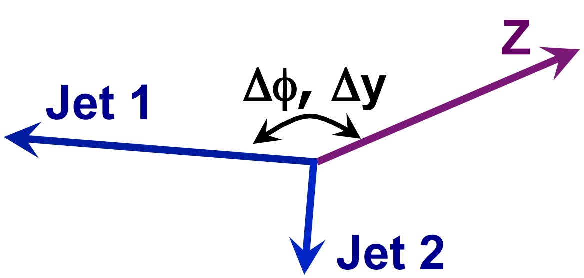
First measurement of angular correlations between Z and leading jet

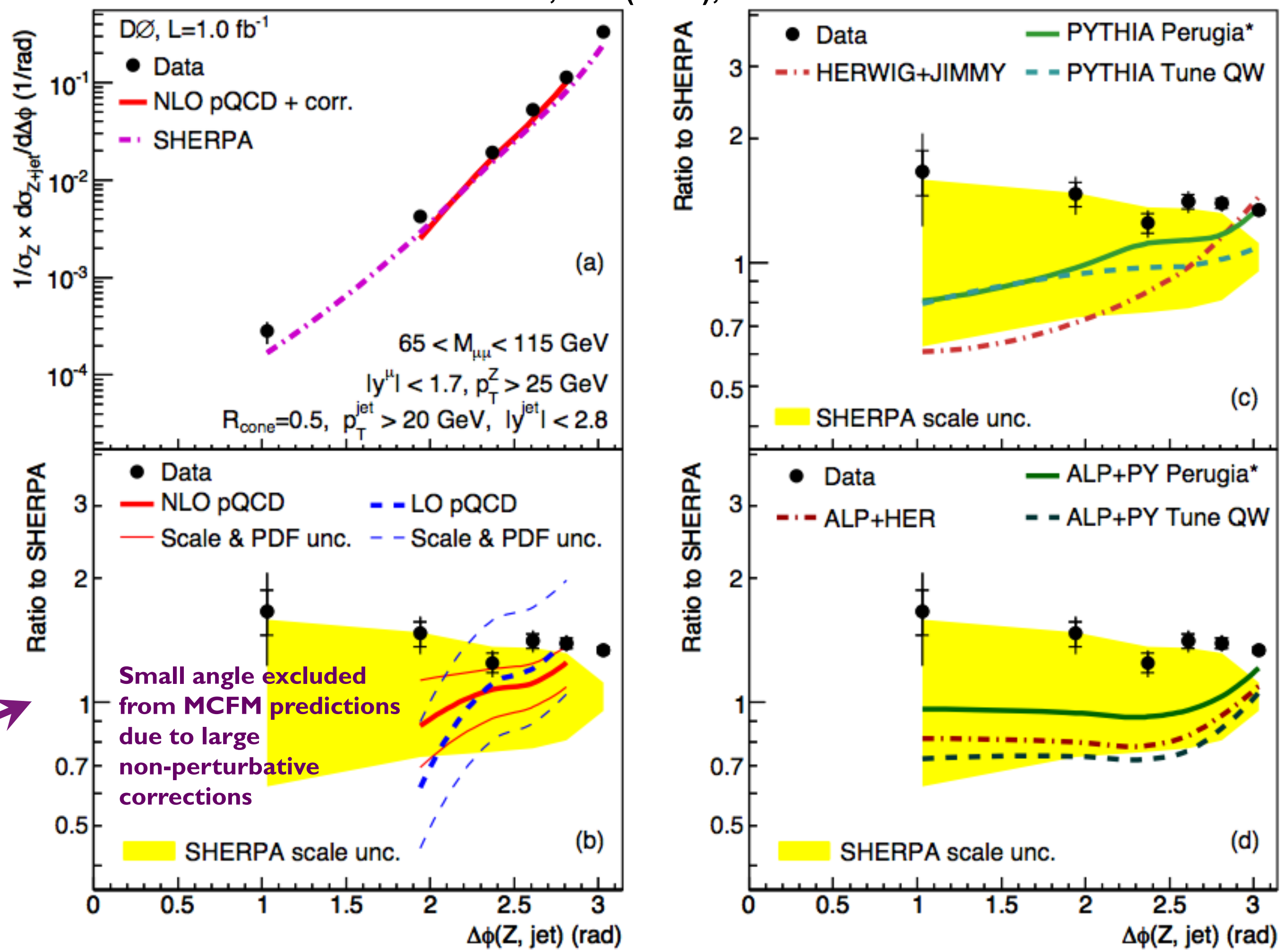
$Z\rightarrow\mu\mu$: $|y^{\mu}|<1.7$, $p_T^{Z}>25$ GeV, jet $p_T>20$ GeV, $|y^{jet}|<2.8$, $R_{cone} = 0.5$

PHYS. LETT. B 682, 370 (2010), ARXIV:0907.4286

Sensitive to additional QCD radiation:

- **Can probe LO and NLO pQCD corrections without requirement of extra reconstructed jets**
- **Sensitive to jets below reco threshold**





Z+jets angular observables: Δy(Z,j)

NLO pQCD and Sherpa do good job of describing shape of Δy(Z,j)

Pythia also does a reasonable job, unlike in Δϕ(Z,j)

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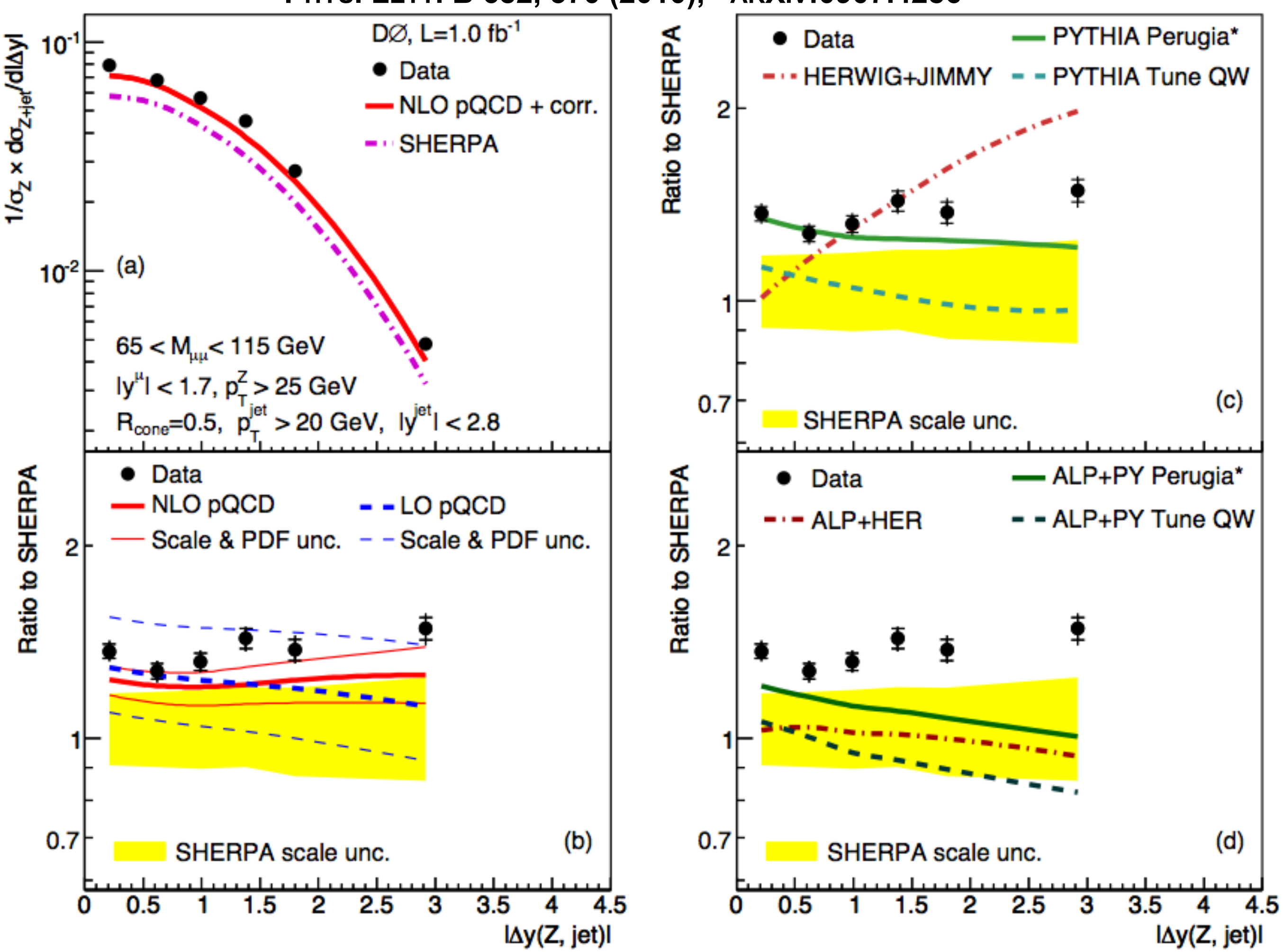


Pythia p_T ordered Perugia* tune MRST07 LO* pdf

Pythia Q^2 ordered

Herwig+Jimmy

Alpgen+Pythia p_T

Alpgen+Herwig

Alpgen+Pythia Q^2

$\sigma(Z+b)/\sigma(Z+jets)$ measurement

Ratio of inclusive Z+b to Z+jets cross-sections

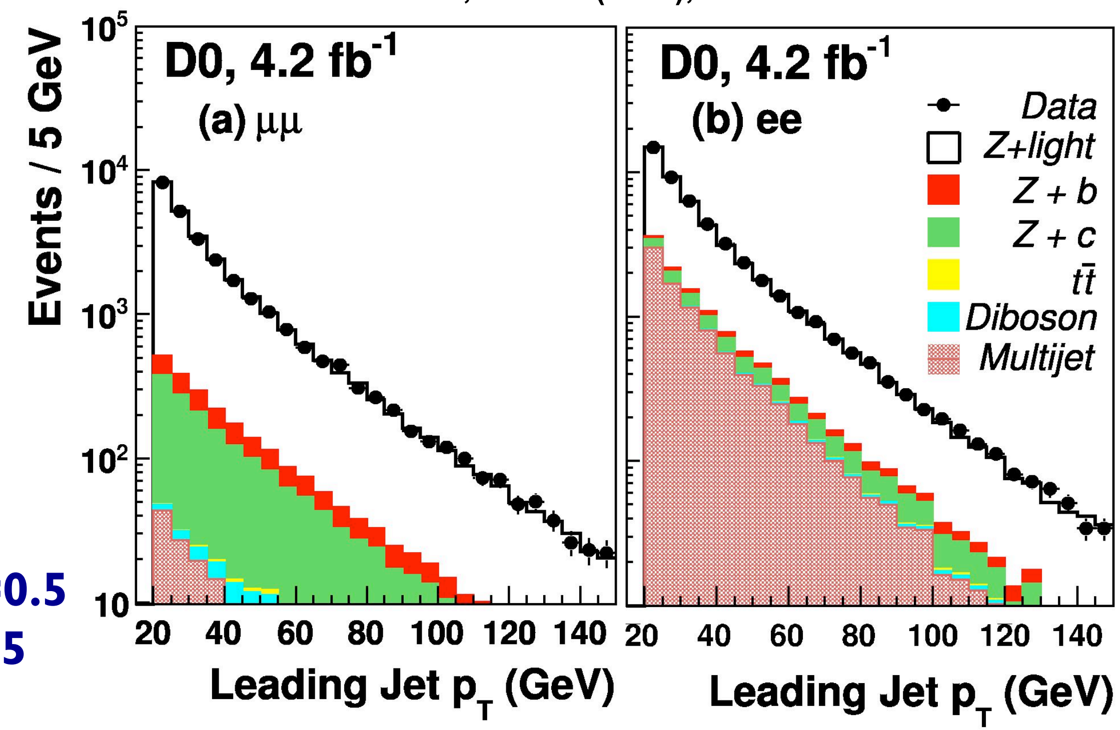
- Test of pQCD calculations and b-quark fragmentation
- Particularly important background to SM Higgs search in ZH(→bb) channel
- Probe of b-quark parton distribution function
- Ratio allows for cancellation of many systematics and precise comparison with theoretical predictions

Challenging as Z+b rate is relatively low, extraction difficult

Study both di-electron and di-muon channels

Lepton p_T>15 GeV,
DØ RunII Midpoint cone R=0.5
Jet p_T>20{15} GeV, jet $|\eta|$<2.5

PHYS. REV. D 83, 031105 (2011), ARXIV:1010.6203

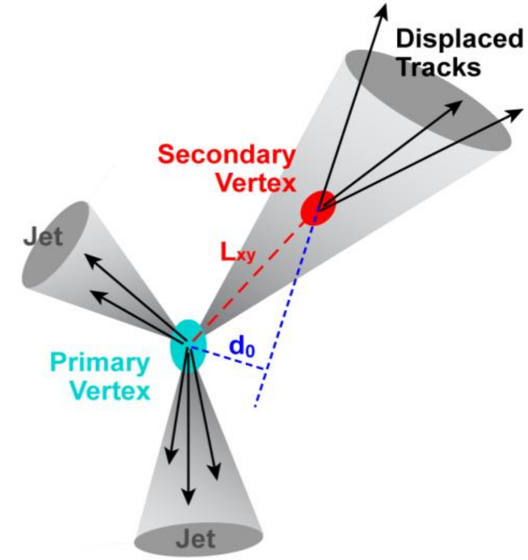


σ(Z+b)/σ(Z+jets) method

Measurement uses neural network based b-tagging algorithm.

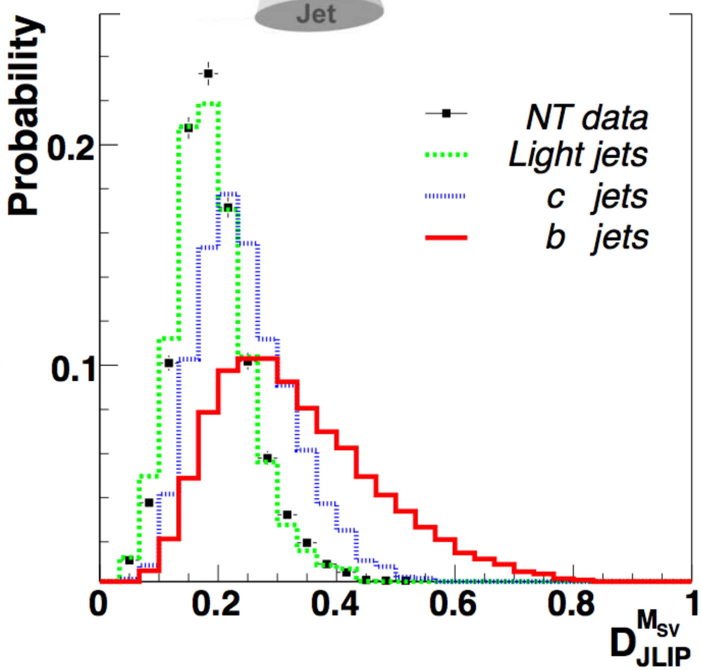
Inputs include: B-lifetime, secondary vertices, vertex mass, & decay length significance…

Tag efficiency: 58%, mis-tag rate: 2%



Further distinguish b-jets from charm/light flavour combining NN output with secondary vertex mass:

- Beauty and charm templates of this discriminant come from Monte Carlo
- Light templates from light-jet enriched data sample from Negative-Tagged (NT) NN data



Unbinned maximum likelihood fit of templates to extract data flavour fractions

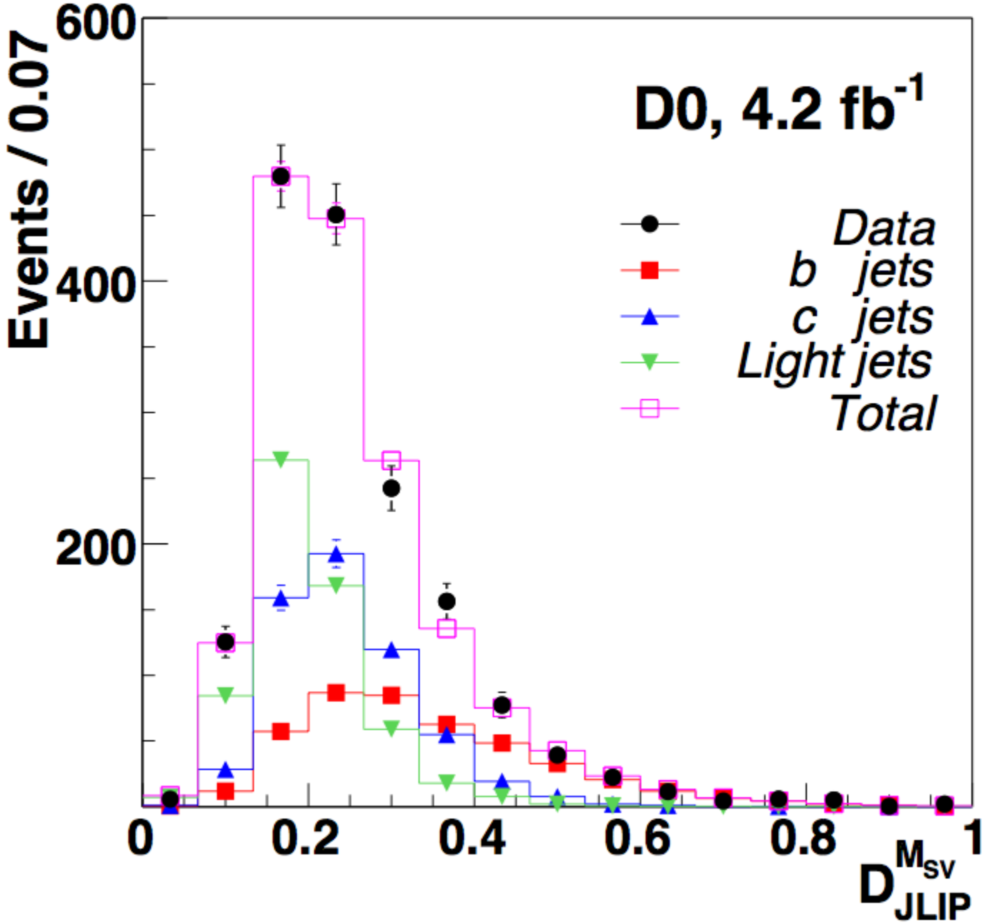
σ(Z+b)/σ(Z+jets) results

Jet flavour fractions measured in both di-electron and di-muon channels

Consistent results in both channels, so combine and re-measure with independent fit

Light/charm discrimination not significant, but b-jet fraction insensitive to light/charm correlations

Phys. Rev. D 83, 031105 (2011), arXiv:1010.6203



Largest systematics come from discriminant template shape (4.2%) and efficiency uncertainties (3.7%)

Measured (Z+b)/(Z+jet):

0.0192±0.0022(stat)±0.0015(syst)

Most precise to-date

Good agreement with MCFM:

0.0185±0.022

W+jets cross-section measurements

New results for this conference on 4.2 fb^{-1} dataset:

- **Measurement of inclusive W+(n)jets cross-sections for n=0—4**
- **Inclusive cross-section ratio σ_n/σ_{n-1} for n=1—4**
- **Differential cross-section measurement of n^{th} (p_T-ordered) jet p_T in inclusive n^{th} jet multiplicity bin**

W candidate identified from high p_T electron + missing E_T
(Electron p_T>15 GeV, $|\eta^e|$<1.1, MET>20 GeV, $m_T(W)$>40 GeV, 2nd lepton veto)

Jets are reconstructed with the DØ RunII Midpoint Cone algorithm
(jet p_T>20 GeV, $|y^{jet}|$<3.2, ΔR(e,jet)>0.5, R_{cone} = 0.5, two associated tracks to PV)

- **Fully correct observables for instrumental effects to particle-level.**
- **Compare to Blackhat+Sherpa and Rocket+MCFM NLO/LO predictions**
- **Use non-pQCD corrections (for UE and hadronization) from Sherpa to correct these predictions from parton to particle level**

W+jets backgrounds and modelling

Signal (W+jets) and backgrounds modelled in Monte Carlo

All MC was hadronised/showered using Pythia 6.403 with following provisos:

- W/Z+jets: uses Alpgen v2.11 with MLM matching and W/Z p_T reweighting to NLO (light and heavy flavour)
- NLO K-factors applied for top and W/Z+jets production
- Top production with Alpgen+Pythia
- Single top simulated with CompHep

Data-driven 'matrix method' used to determine QCD Multijet background (where electron fakes a jet)

Fake rate (binned in jet multiplicity, lepton eta, lepton p_T)

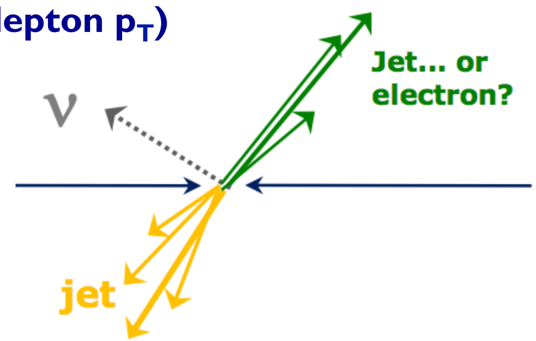
$$N_{QCD}^{tight} = \left(\frac{\varepsilon_{QCD}}{(1-\varepsilon_{QCD})}\right) N_{LNT} - \left(\frac{(1-\varepsilon_{sig})}{\varepsilon_{sig}}\right)\left(\frac{\varepsilon_{QCD}}{(1-\varepsilon_{QCD})}\right) N_{tight}$$

Multijet distribution

Loose-not-Tight distribution

Signal selection sample

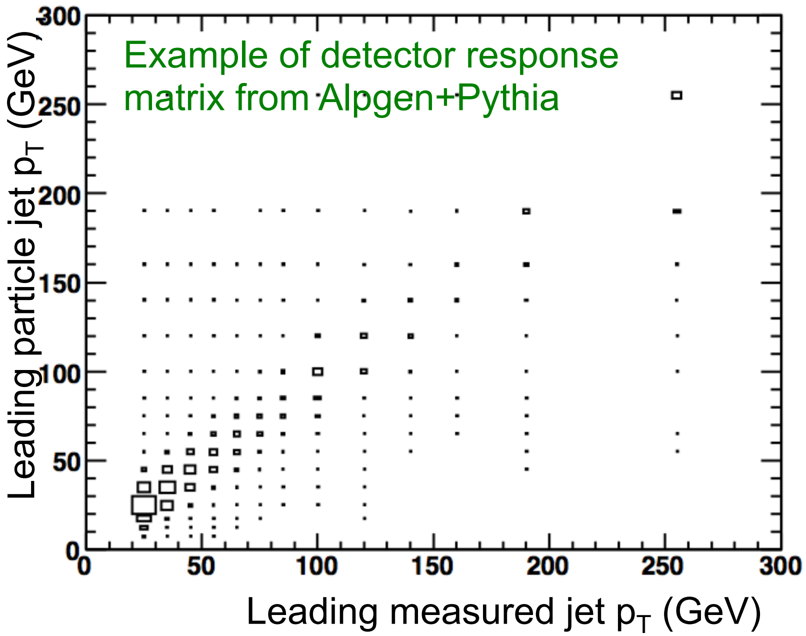
Real electron efficiency (binned in lepton eta, lepton p_T)



Unfolding procedure is performed using the GURU program using a Singular Value Decomposition technique ***(NIM A 372, 469; hep-ph/9509307)***

Inputs are background-subtracted data distributions, Monte Carlo reco-level distributions and MC derived detector response matrices

Used to produce acceptance corrections and unfold detector effects



- **SVD unfolding offers better treatment of bin migrations and statistical uncertainties where off-diagonal elements of response matrix are large**
- **Significantly reduces dependence on MC description of signal/background over bin-by-bin corrections**

Derivation of inclusive W cross-section

Pre-selection provides W inclusive sample of 2.2M events with low background (<1%)

Backgrounds again simulated with MC and data-derived methods (for QCD multijet): incorporate these into systematic on measurement

Correct data to particle-level for detector efficiencies, using acceptance corrections from Alpgen+Pythia:

$$\frac{1}{\sigma_W} = \frac{\mathcal{L}}{N_{\mathrm{DATA}}^{\mathrm{reco}}} \cdot \frac{N_{\mathrm{MC}}^{\mathrm{reco}}}{N_{\mathrm{MC}}^{\mathrm{truth}}}$$

Choose to normalize jet results to inclusive W cross-section, for cancellation or reduction of some systematics

W+jet experimental uncertainties

In addition to Jet Energy Scale [4—16%] example shown on previous slide, also determine systematics in same manner for:

- **Jet Energy Resolution [2—10%]**
- **Jet Vertex Confirmation (tracks associated to PV) [2—8%]**
- **JetID efficiency [0.5—4%]**
- **Trigger efficiency [<1%]**

And additional studies to determine systematic effect of:

- **Electron ID [1%]**
- **Background modelling uncertainties [0.5—20%]**
  (and impact of detector systematics on backgrounds)
- **Unfolding MC model dependence [0.2—2%]**
- **Unfolding bias determination/correction uncertainty [0.1—1%]**
- **Lumi uncertainty & dependence on instantaneous lumi [~0%]**
- **Electron final state radiation [<1%]**

Comparison with pQCD theory

Compare unfolded inclusive and differential cross-section results to perturbative QCD NLO precision calculations from two different groups/approaches:

Rocket+MCFM and Blackhat+Sherpa

As well as differences in approach to calculation, there are differences in PDF, and in renormalisation/factorisation scale choice:

Blackhat collaboration choose $\frac{1}{2}H_T$
(half the scalar sum of parton+lepton transverse energies from hard interaction)

Rocket collaboration choose dynamical scale: $\sqrt{M_W^2 + \frac{1}{4}(\sum p_j)^2}$
where p_j are the 4-momenta of the jets

and a modified scale choice of $\sqrt{M_W^2 + (\sum p_T^{\mathrm{jet1}})^2}$ **in the one-jet case.**

Apply non-perturbative corrections for underlying event and hadronization effects, derived from Sherpa 1.2.3 and CTEQ6.6 PDF to bring pQCD calculations to particle-level

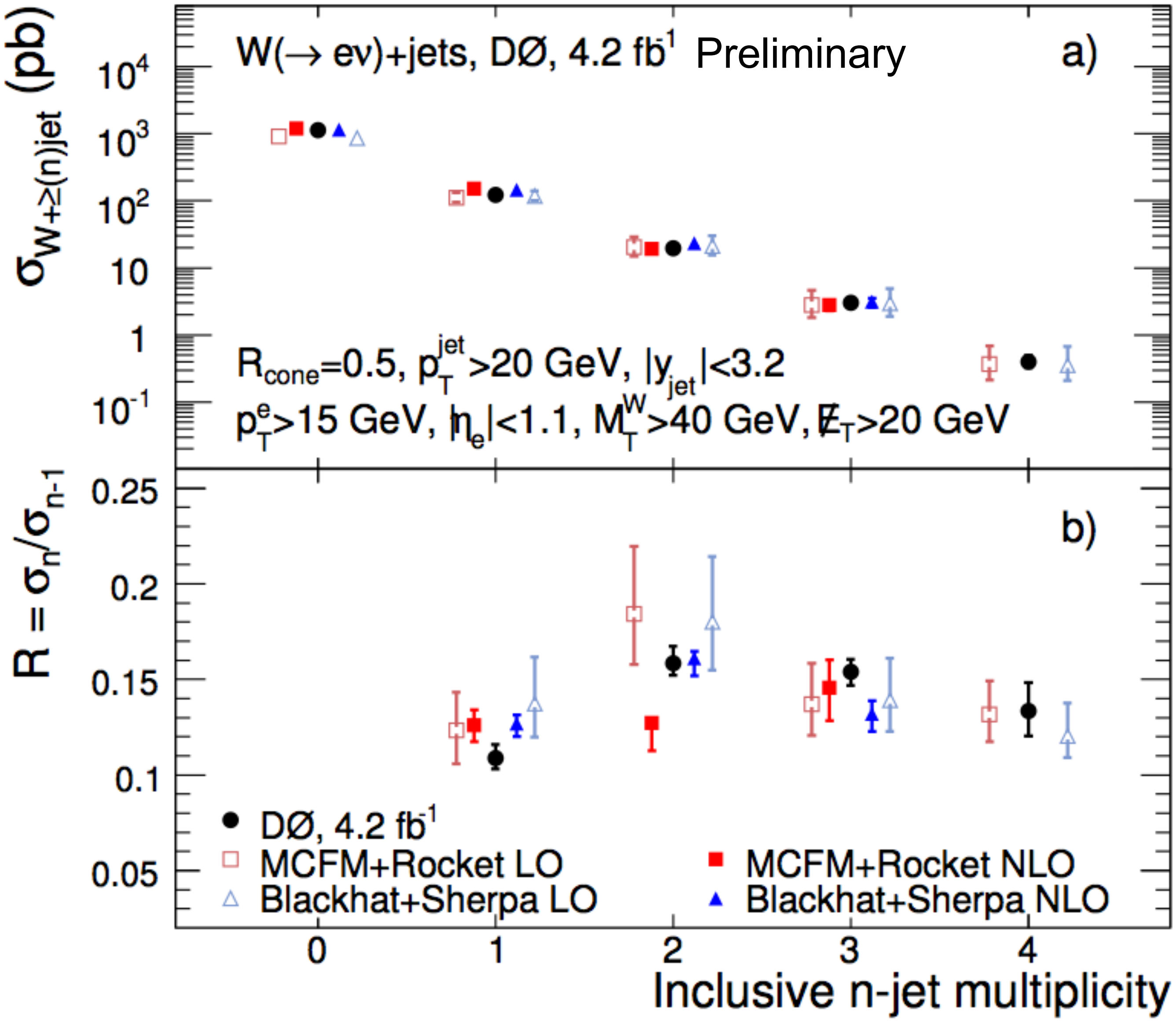
Inclusive cross-section results W+jets

Data precision greater than best pQCD predictions available (ratio and absolute)

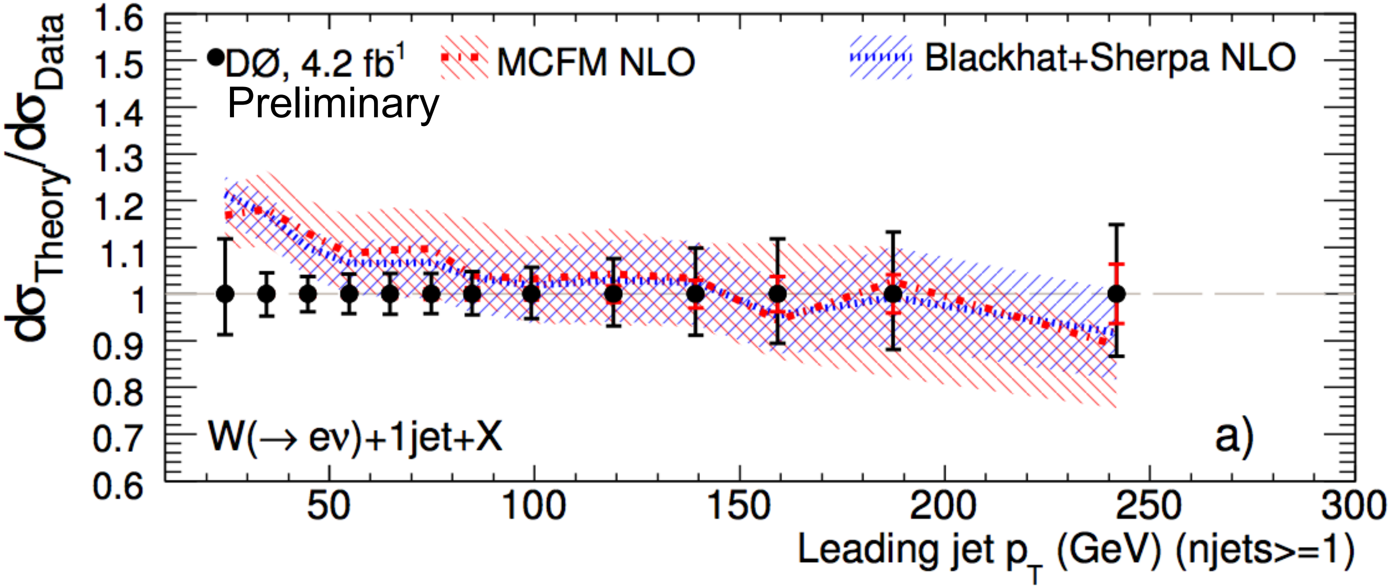
Non-perturbative inclusive corrections to pQCD are +0/6/10/11/16% derived with Sherpa 1.2.3

Benefit from many uncertainties cancelling in the ratio

Breakdown of MCFM +Rocket W+2j scale choice evident



Differential cross-section results (W+jet 1)



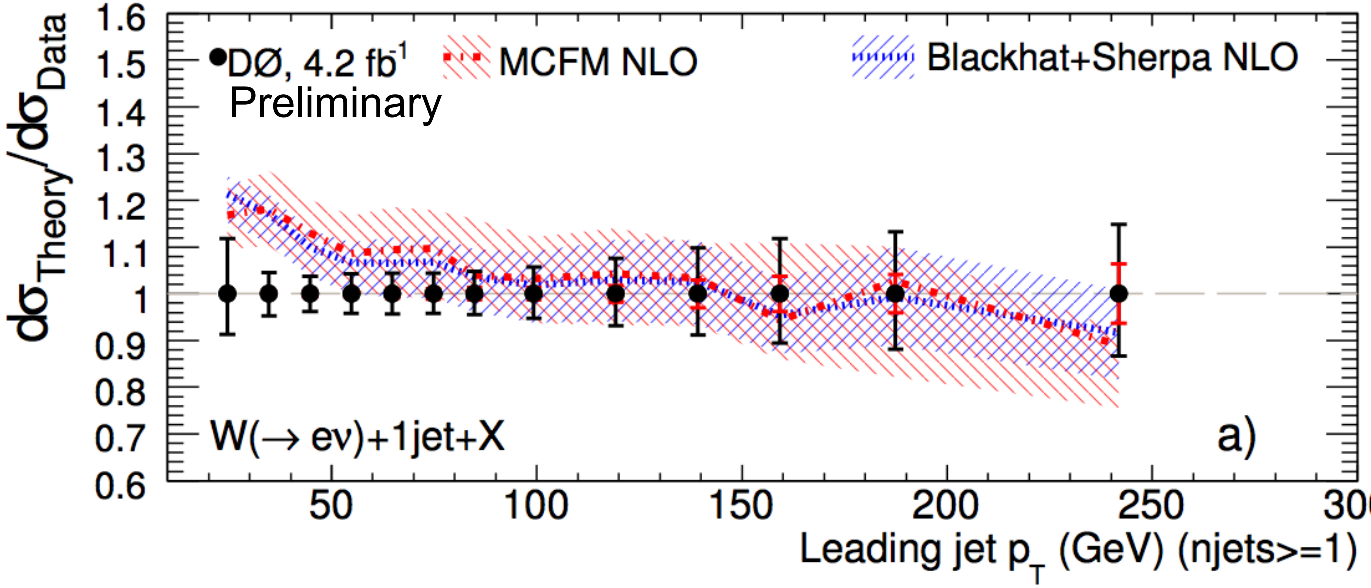
Leading jet p_T in W+1jet inclusive events: plot shows ratio of theory to data, each normalised by their respective inclusive W cross-sections

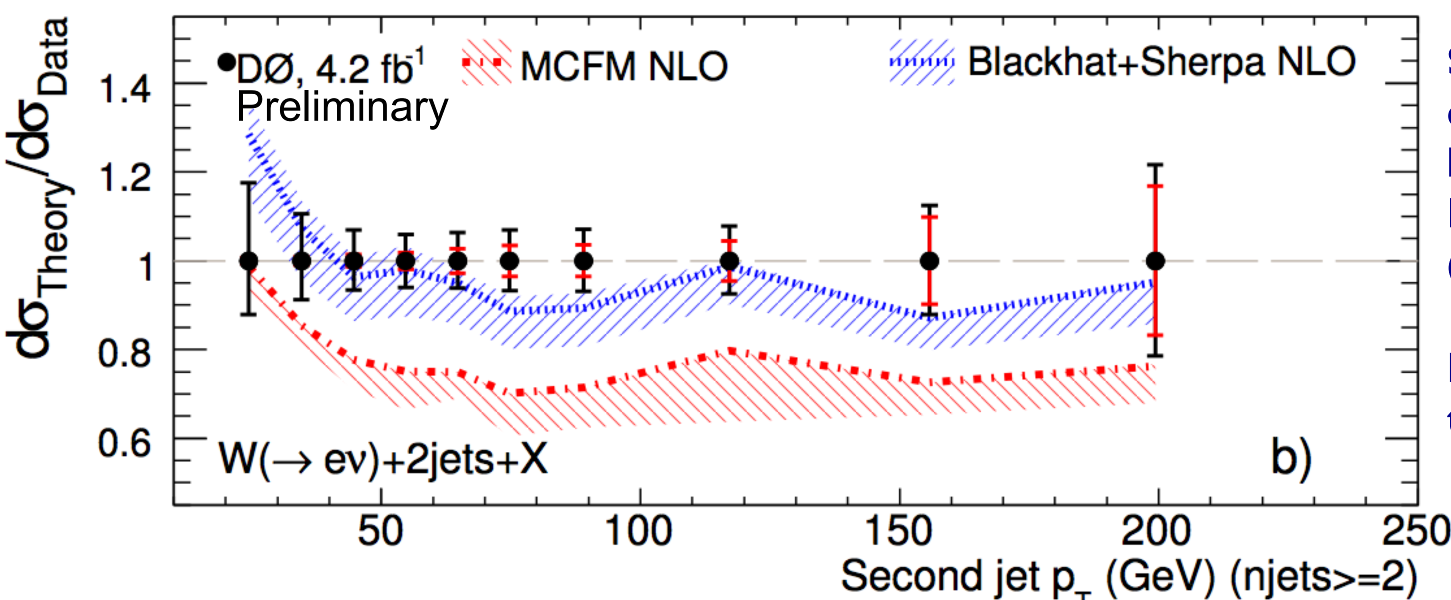
$$\frac{1}{\sigma_W^{\text{theory}}} \cdot \frac{d\sigma_{W+(n)j}^{\text{theory}}}{dp_T} \Big/ \frac{1}{\sigma_W^{\text{data}}} \cdot \frac{d\sigma_{W+(n)j}^{\text{data}}}{dp_T}$$

Differential cross-section results (W+jet 1,2)

NLO predictions doing a good job of shape and scale in leading jet p_T, except perhaps at low p_T threshold

Data uncertainties smaller or equivalent to theory



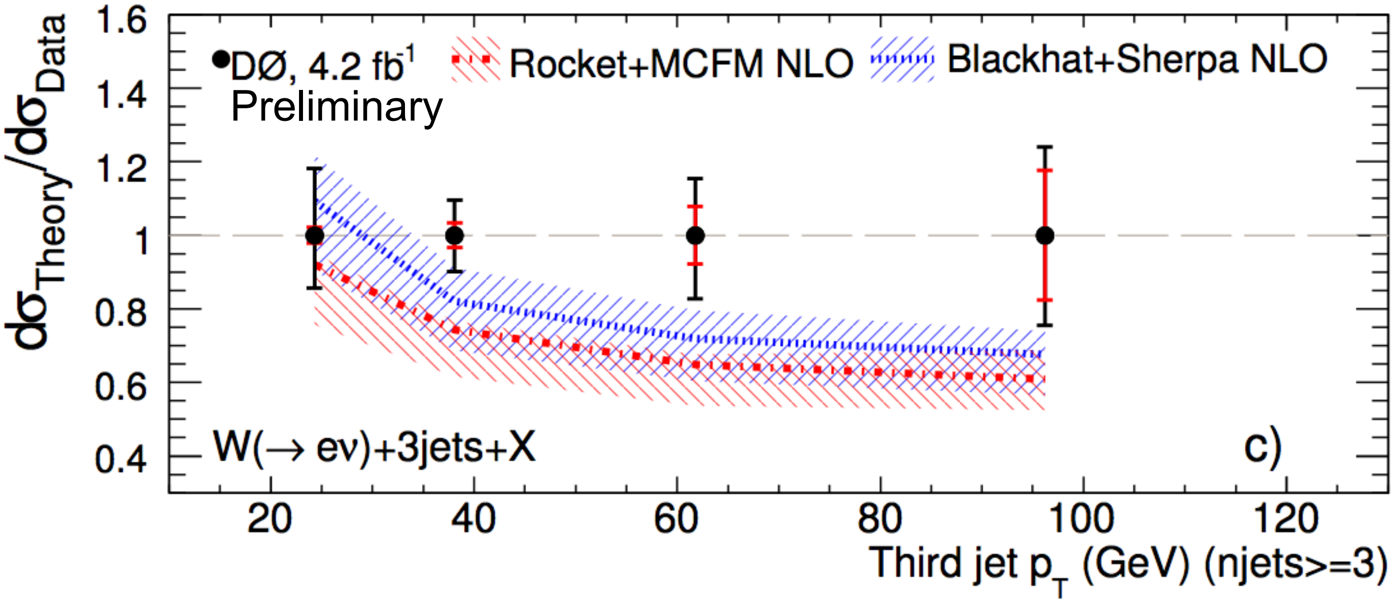


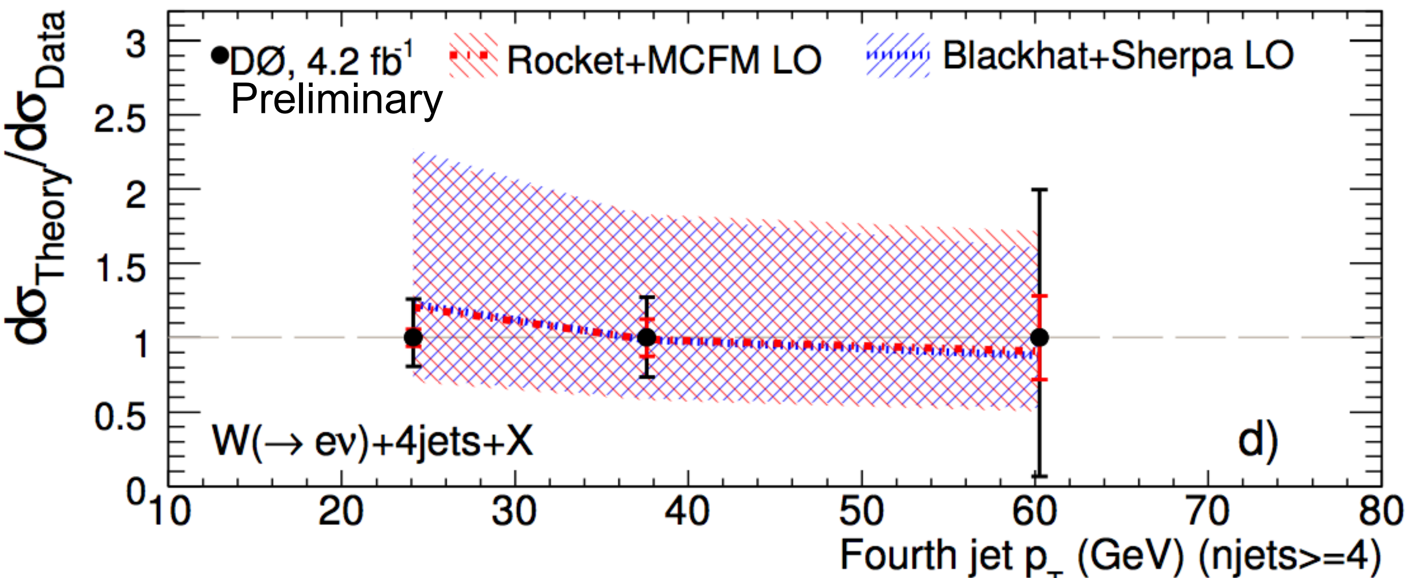
Second jet p_T shows disagreement between MCFM and Blackhat predictions (due to scale choice)

Data precise enough to distinguish

Differential cross-section results (W+jet 3,4)

Third jet shows some disagreement in shape & normalization with NLO – partially due to non-perturbative corrections





Only LO predictions available for W+4j at Tevatron right now

Good agreement within large scale uncertainties

More distributions to come!

Summary

Have presented a small slice of recent W/Z+jets results produced by the DØ Collaboration recently:

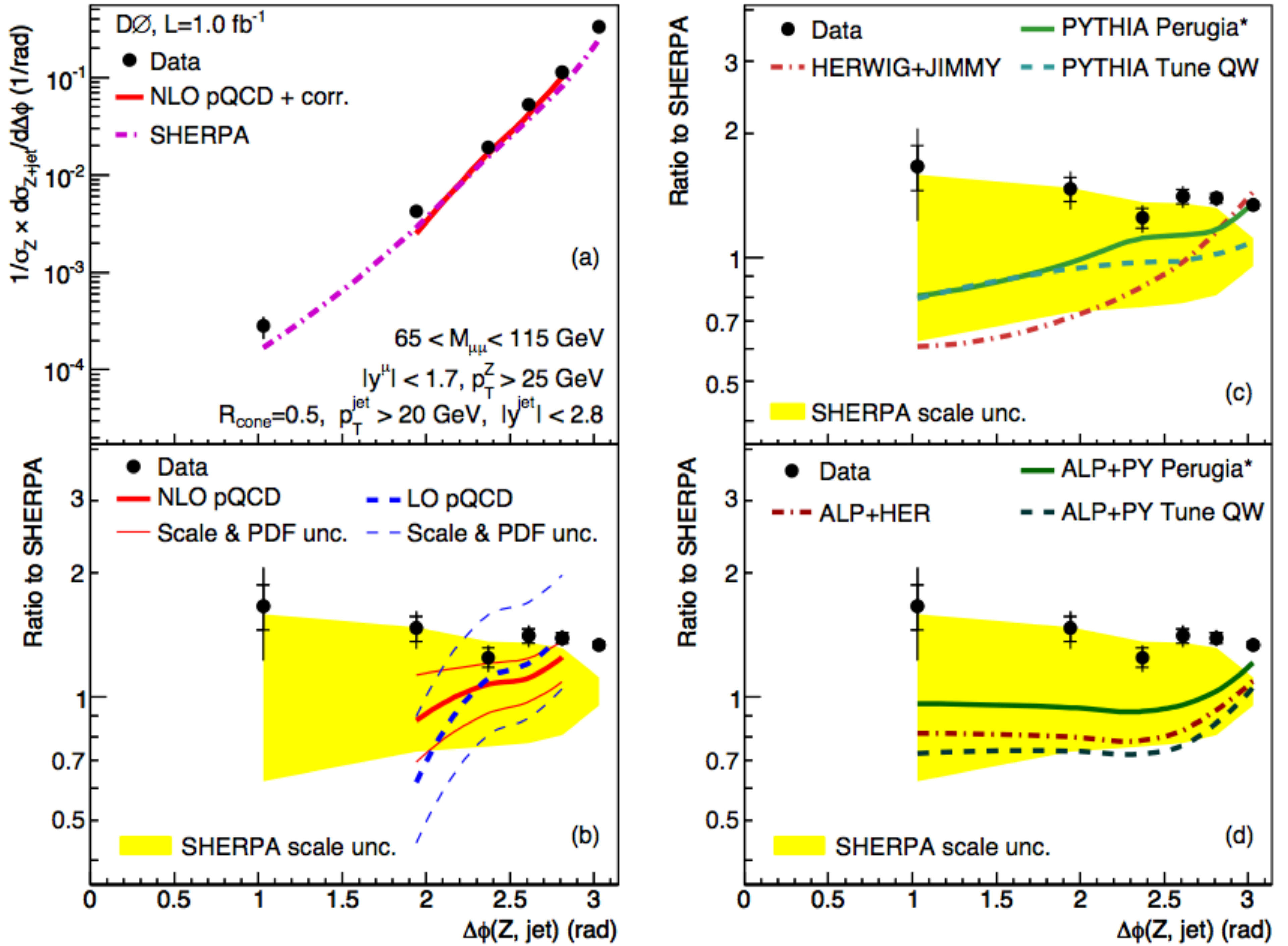
- **Angular correlations in Z+jet events**
- **Measurement of the Z+b/Z+jet fraction**
- **Inclusive & differential cross-section measurements of W+jet events with up to four jets**

Comparisons made to NLO(LO) pQCD and Monte Carlo generators:

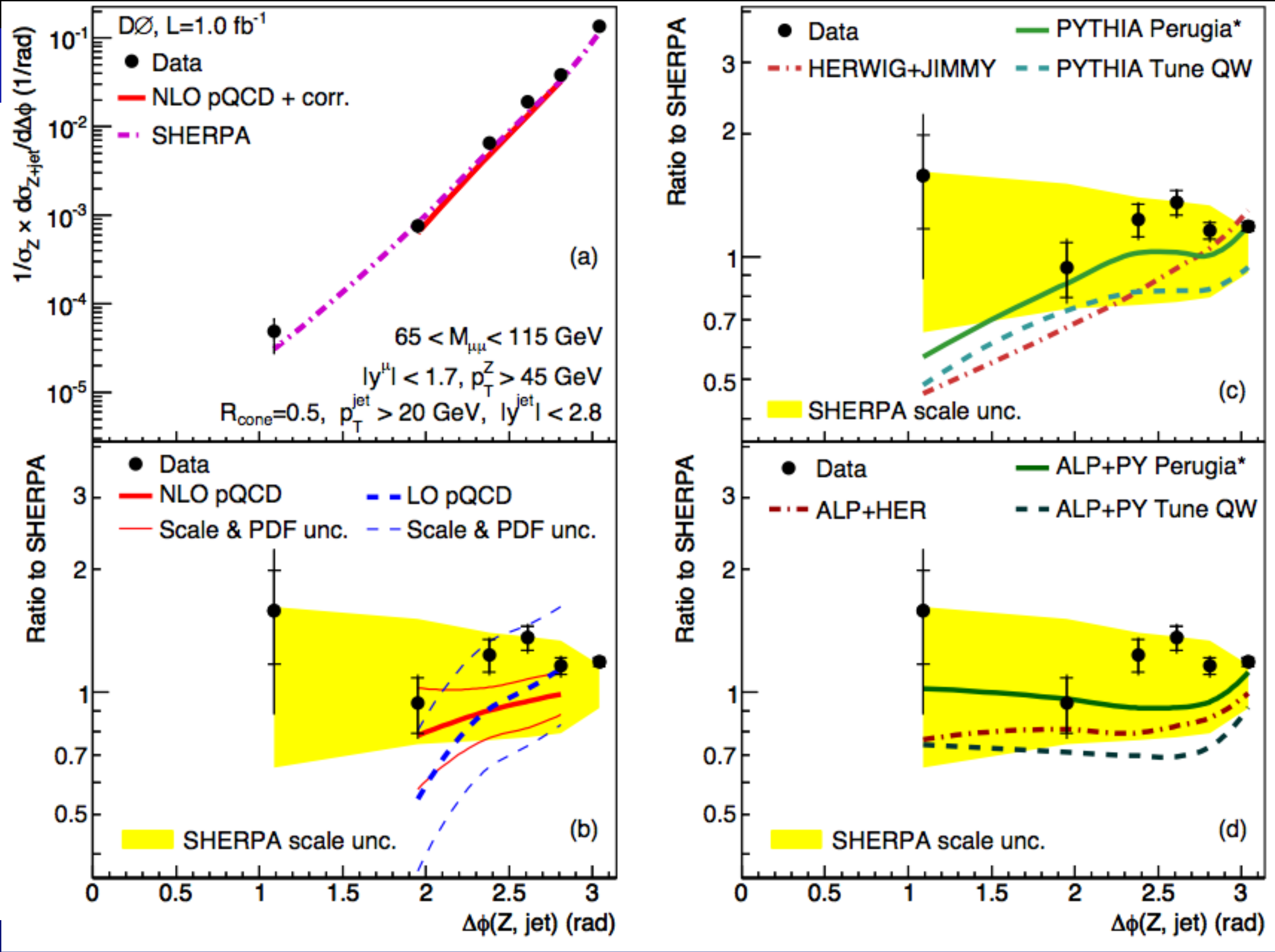
- **On the whole, good agreement with data, but some discrepancies observed**
- **Data uncertainties are now smaller or comparable to the best pQCD calculations available**
- **Some discrepancies seen *between* theoretical approaches: DØ measurements are sensitive enough to provide input in these cases**

Have large, well-understood datasets that will now be used to provide a variety of W/Z+jets measurements in the near future

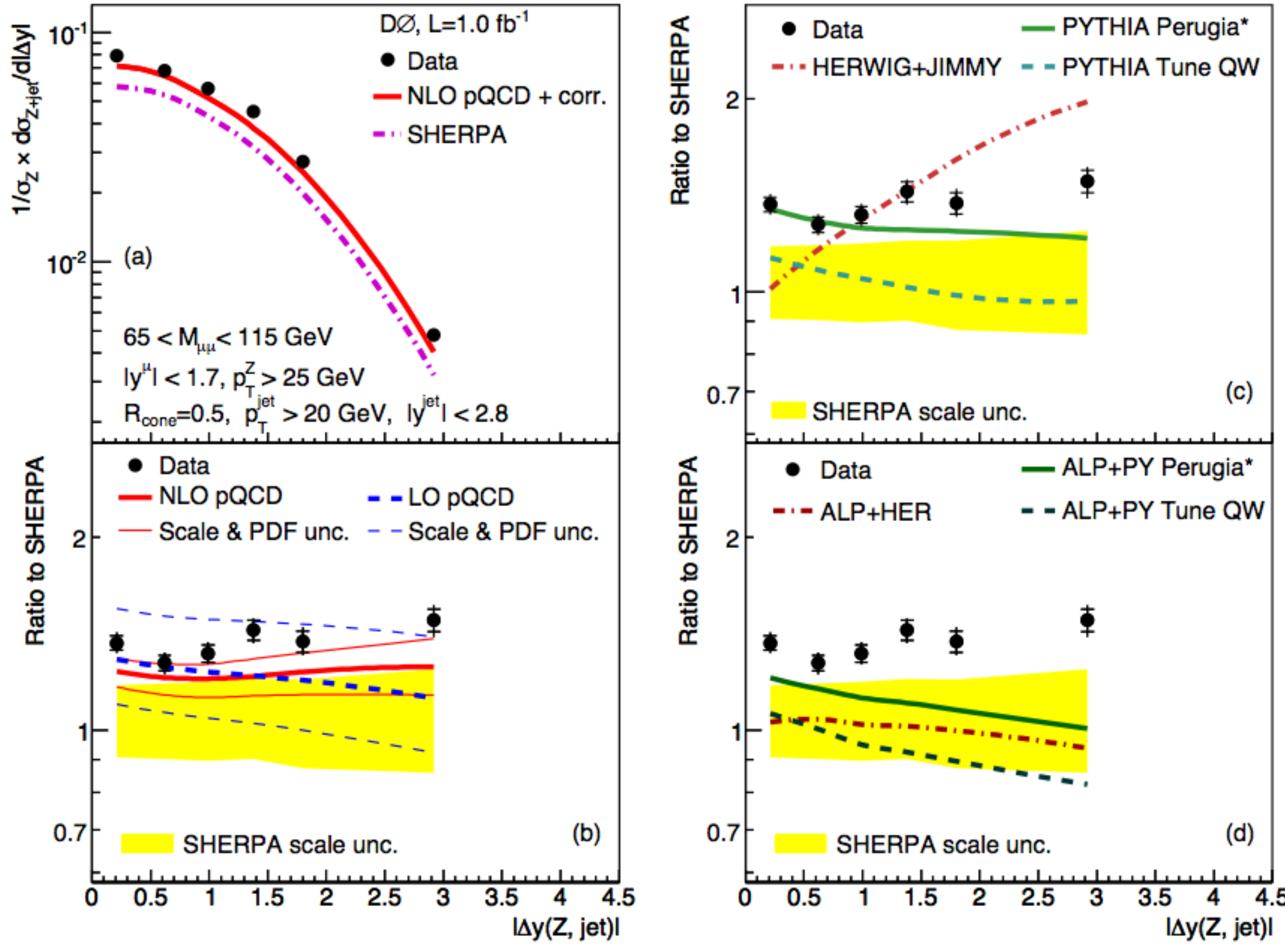
Additional slides



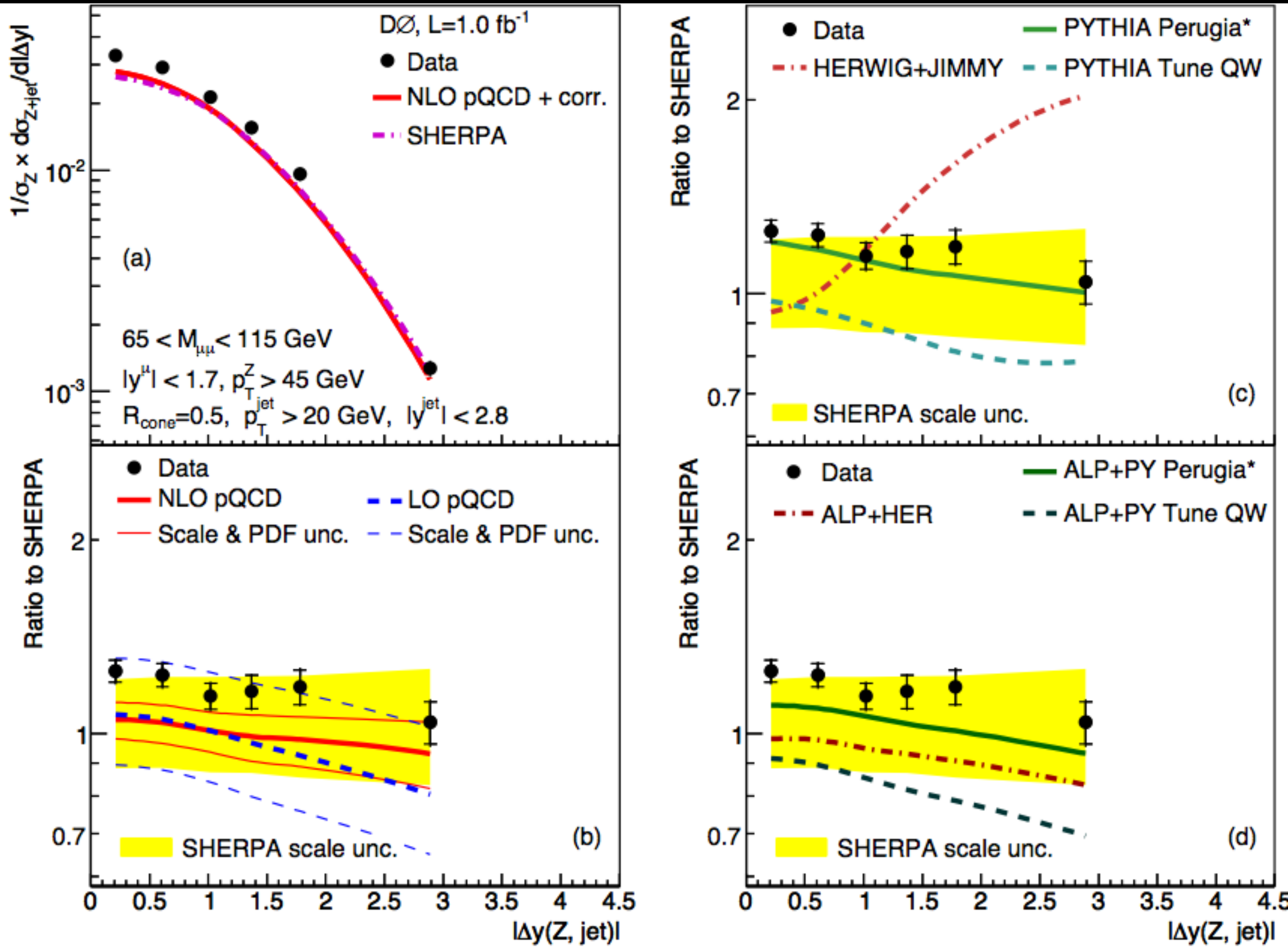
DØ, L=1.0 fb-1
Data
NLO pQCD + corr.
SHERPA
1/σZ × dσZ+jet/dΔφ (1/rad)
(a)
65 < Mμμ < 115 GeV
|yμ| < 1.7, pTZ > 25 GeV
Rcone=0.5, pTjet > 20 GeV, |yjet| < 2.8
Data
PYTHIA Perugia*
HERWIG+JIMMY
PYTHIA Tune QW
Ratio to SHERPA
SHERPA scale unc.
(c)
Data
NLO pQCD
LO pQCD
Scale & PDF unc.
Scale & PDF unc.
SHERPA scale unc.
(b)
Data
ALP+PY Perugia*
ALP+HER
ALP+PY Tune QW
SHERPA scale unc.
(d)
Δφ(Z, jet) (rad)
Δφ(Z, jet) (rad)

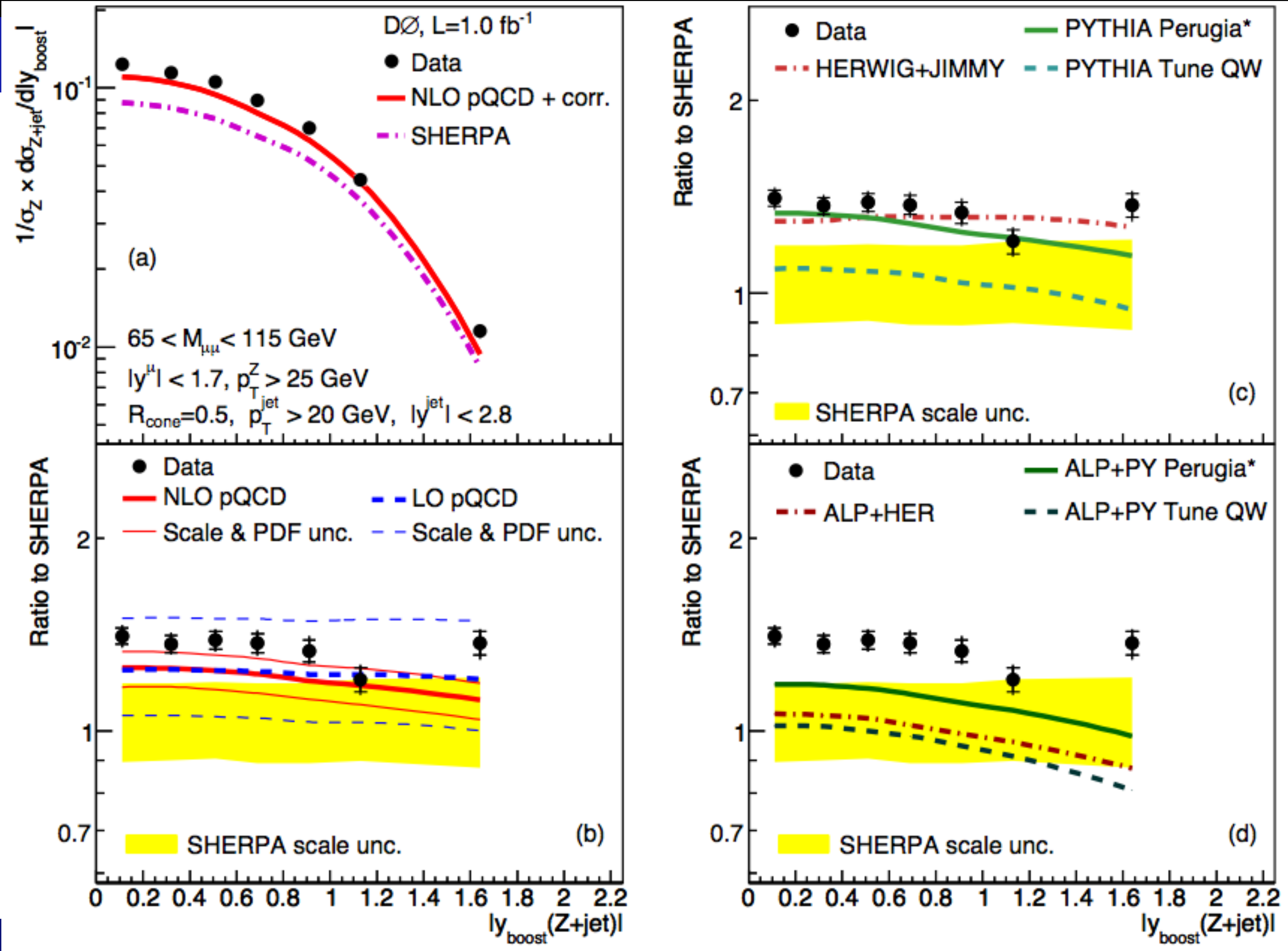


DØ, L=1.0 fb^{-1}
Data
NLO pQCD + corr.
SHERPA
$1/\sigma_Z \times d\sigma_{Z+jet}/d\Delta\phi$ (1/rad)
(a)
$65 < M_{\mu\mu} < 115$ GeV
$|y^{\mu}| < 1.7$, $p_T^Z > 45$ GeV
$R_{cone}=0.5$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.8$
Data
PYTHIA Perugia*
HERWIG+JIMMY
PYTHIA Tune QW
Ratio to SHERPA
(c)
SHERPA scale unc.
Data
NLO pQCD
LO pQCD
Scale & PDF unc.
Scale & PDF unc.
Ratio to SHERPA
(b)
SHERPA scale unc.
$\Delta\phi$(Z, jet) (rad)
Data
ALP+PY Perugia*
ALP+HER
ALP+PY Tune QW
Ratio to SHERPA
(d)
SHERPA scale unc.
$\Delta\phi$(Z, jet) (rad)

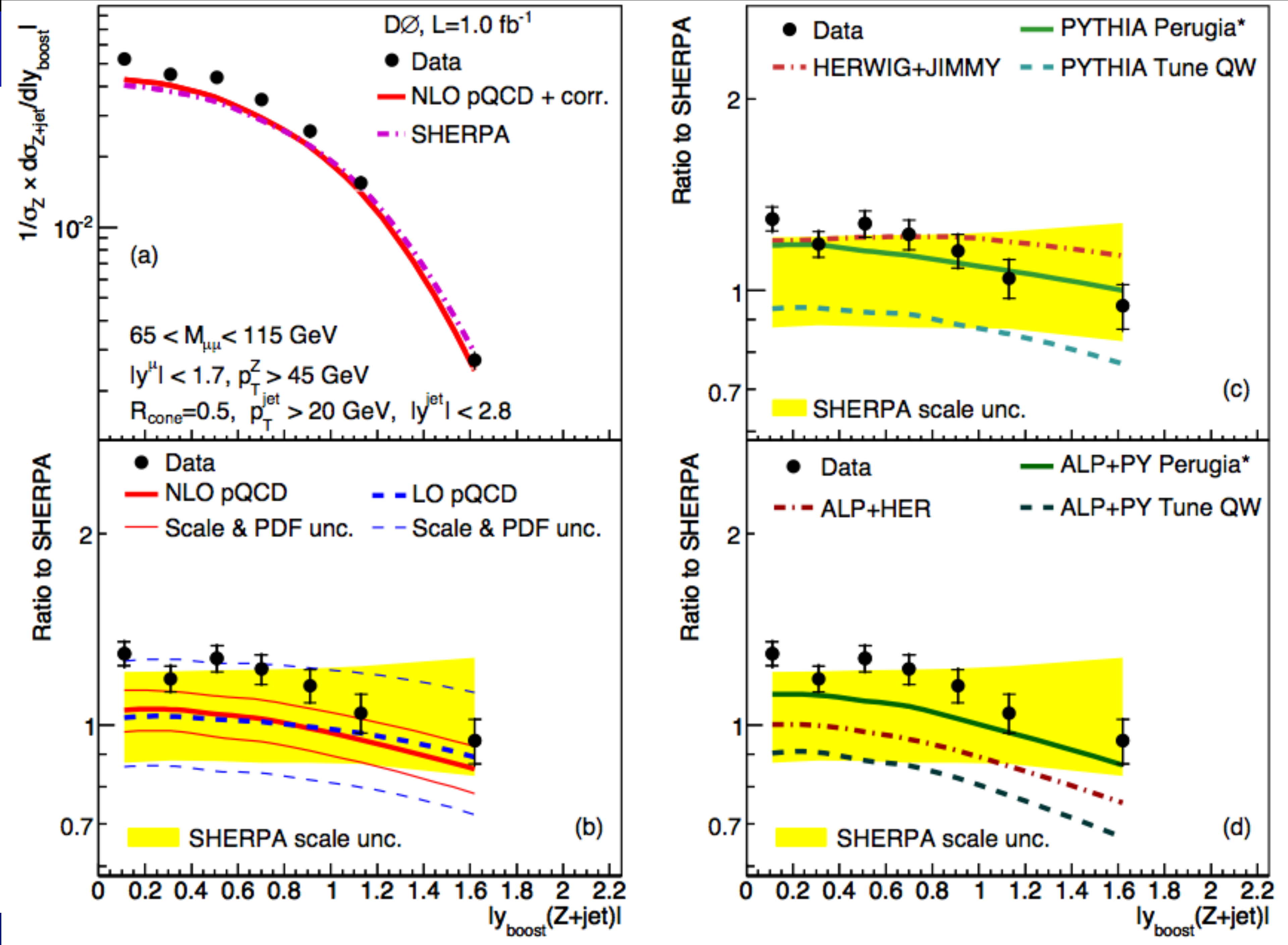


DØ, L=1.0 fb-1
Data
NLO pQCD + corr.
SHERPA
1/σZ × dσZ+jet/d|Δy|
(a)
65 < Mμμ < 115 GeV
|yμ| < 1.7, pTZ > 25 GeV
Rcone=0.5, pTjet > 20 GeV, |yjet| < 2.8
Data
PYTHIA Perugia*
HERWIG+JIMMY
PYTHIA Tune QW
Ratio to SHERPA
SHERPA scale unc.
(c)
Data
NLO pQCD
LO pQCD
Scale & PDF unc.
Scale & PDF unc.
Ratio to SHERPA
SHERPA scale unc.
(b)
|Δy(Z, jet)|
Data
ALP+PY Perugia*
ALP+HER
ALP+PY Tune QW
Ratio to SHERPA
SHERPA scale unc.
(d)
|Δy(Z, jet)|


DØ, L=1.0 fb⁻¹
Data
NLO pQCD + corr.
SHERPA
(a)
65 < Mμμ < 115 GeV
|yμ| < 1.7, pTZ > 45 GeV
Rcone=0.5, pTjet > 20 GeV, |yjet| < 2.8
1/σZ × dσZ+jet/d|Δy|
Data
HERWIG+JIMMY
PYTHIA Perugia*
PYTHIA Tune QW
SHERPA scale unc.
(c)
Ratio to SHERPA
Data
NLO pQCD
Scale & PDF unc.
LO pQCD
Scale & PDF unc.
SHERPA scale unc.
(b)
Data
ALP+HER
ALP+PY Perugia*
ALP+PY Tune QW
SHERPA scale unc.
(d)
|Δy(Z, jet)|



DØ, L=1.0 fb^{-1}
Data
NLO pQCD + corr.
SHERPA
$1/\sigma_Z \times d\sigma_{Z+jet}/d|y_{boost}|$
(a)
$65 < M_{\mu\mu} < 115$ GeV
$|y^{\mu}| < 1.7$, $p_T^Z > 25$ GeV
$R_{cone}=0.5$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.8$
Data
PYTHIA Perugia*
HERWIG+JIMMY
PYTHIA Tune QW
Ratio to SHERPA
SHERPA scale unc.
(c)
Data
NLO pQCD
LO pQCD
Scale & PDF unc.
Scale & PDF unc.
Ratio to SHERPA
SHERPA scale unc.
(b)
Data
ALP+PY Perugia*
ALP+HER
ALP+PY Tune QW
Ratio to SHERPA
SHERPA scale unc.
(d)
$|y_{boost}(Z+jet)|$
$|y_{boost}(Z+jet)|$



DØ, L=1.0 fb⁻¹
Data
NLO pQCD + corr.
SHERPA
(a)
$1/\sigma_Z \times d\sigma_{Z+jet}/d|y_{boost}|$
10^{-2}
$65 < M_{\mu\mu} < 115$ GeV
$|y^{\mu}| < 1.7$, $p_T^Z > 45$ GeV
$R_{cone}=0.5$, $p_T^{jet} > 20$ GeV, $|y^{jet}| < 2.8$
Data
PYTHIA Perugia*
HERWIG+JIMMY
PYTHIA Tune QW
SHERPA scale unc.
(c)
Ratio to SHERPA
Data
NLO pQCD
LO pQCD
Scale & PDF unc.
Scale & PDF unc.
SHERPA scale unc.
(b)
Data
ALP+PY Perugia*
ALP+HER
ALP+PY Tune QW
SHERPA scale unc.
(d)
$|y_{boost}(Z+jet)|$

W+jets unfolding biases and systematics

After unfolding the central value of differential cross-sections, there are two questions to address:

1. **Was there any intrinsic bias in the unfolding procedure, and can we correct for it?**
2. **What are the associated systematic/statistical uncertainties on the unfolded results?**

To answer these questions, we use MC-derived ensembles:
In MC we always have access to the true value to compare with unfolded!

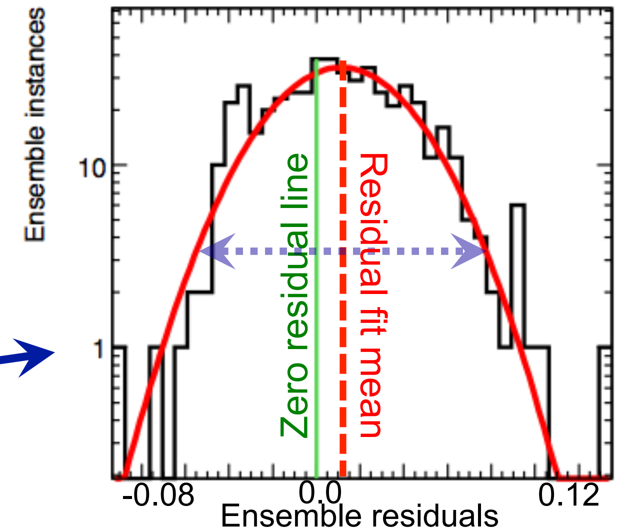
a. Reweight Alpgen+Pythia at particle-level to describe unfolded data

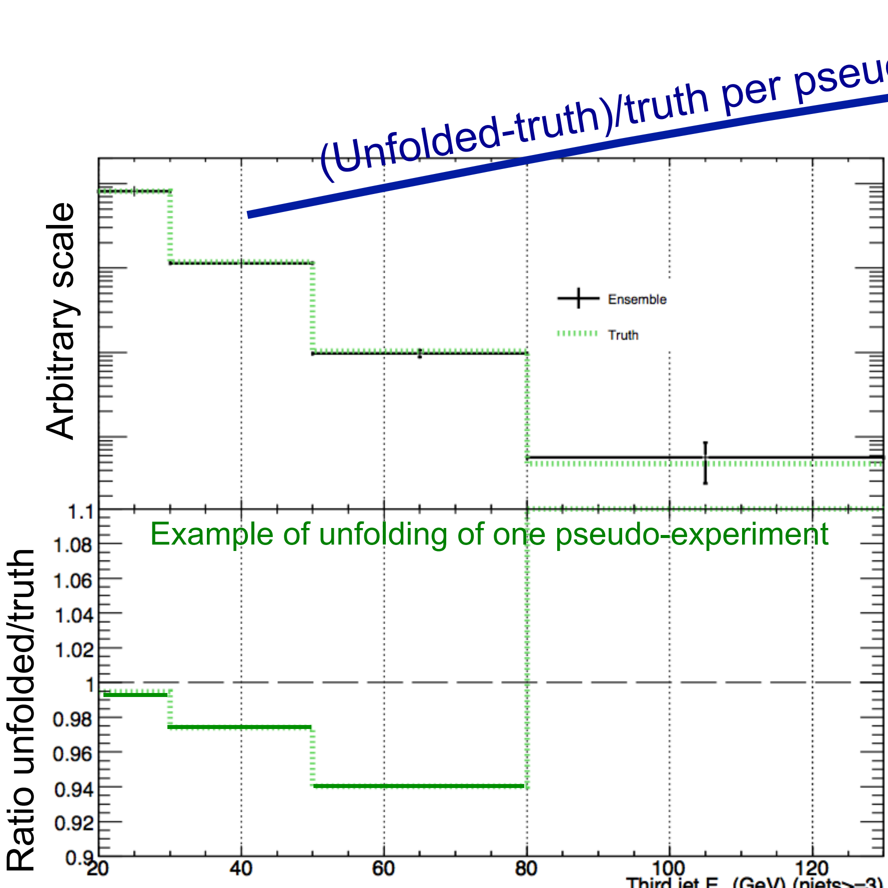
b. Ensure this reweighted MC describes the data at particle and reconstruction levels in distribution of interest

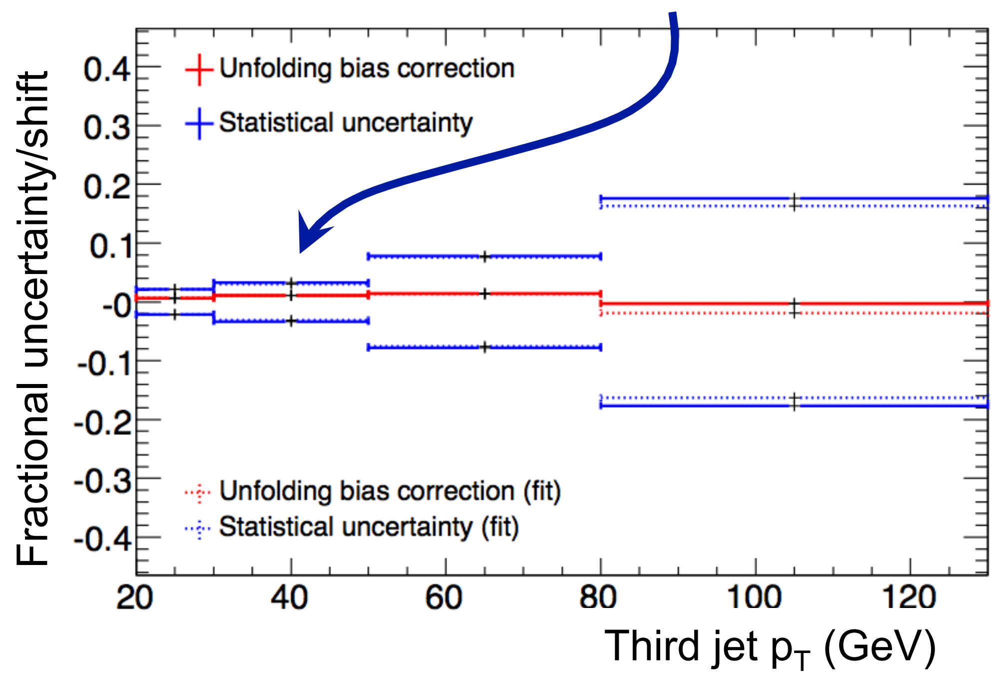
c. Build pseudo-experiments from this MC with *on average* the same statistics and fluctuations as data in total number of events and in the individual bins of the distributions

W+jets unfolding biases and systematics

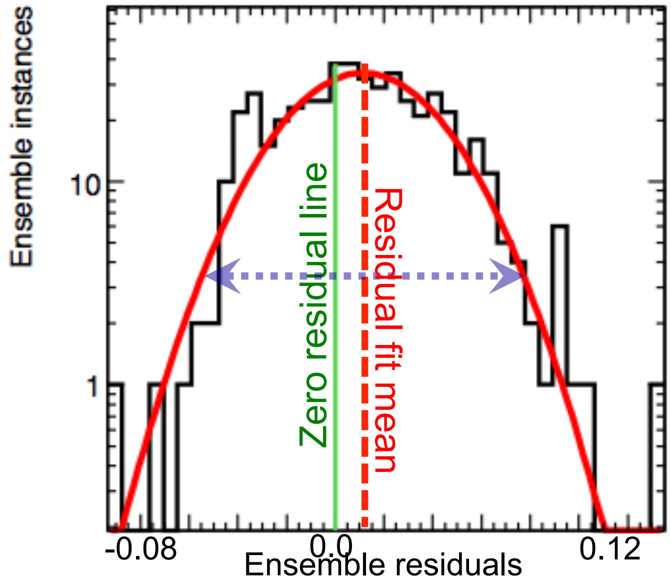
- **Unfold each ensemble under same procedure and same inputs as for data**
- **For each bin in each distribution, build residual**
- **Mean of residual distribution gives bias**
- **Width gives statistical uncertainty**



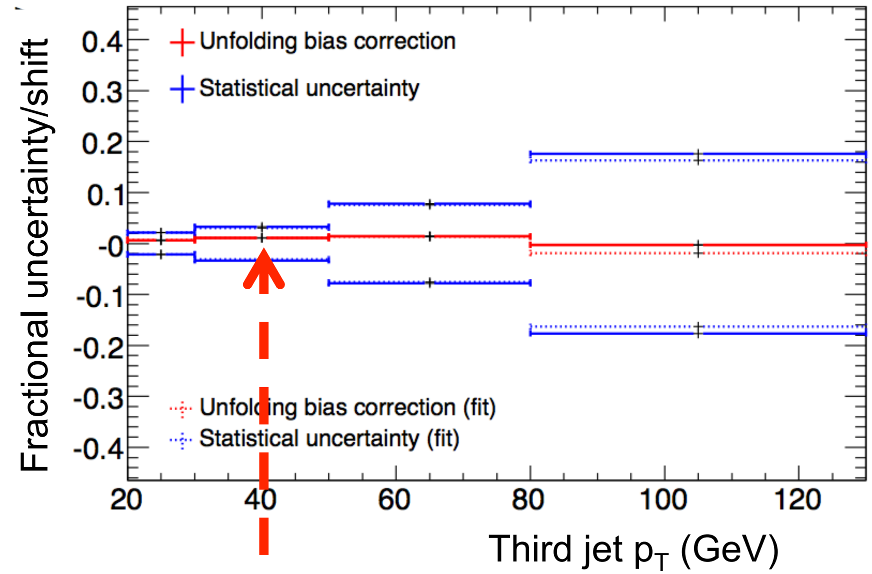


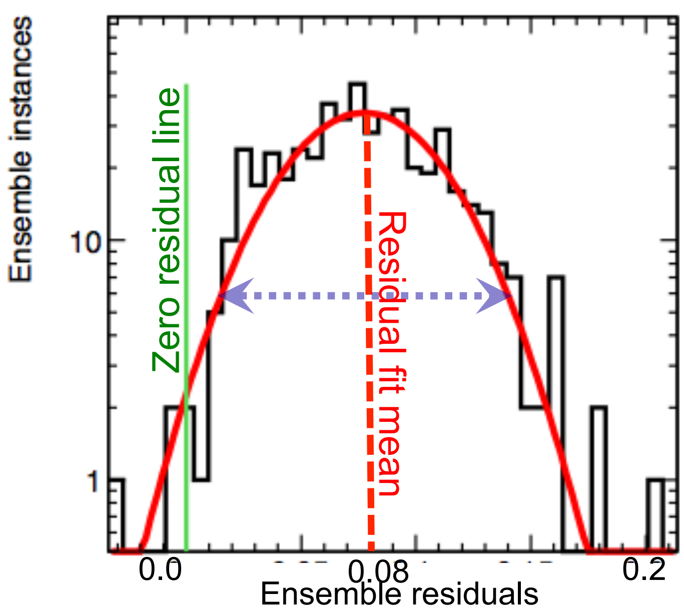


W+jets systematics determination (example)



NOMINAL UNFOLDING





INPUTS TO UNFOLDING WITH JES UNCERTAINTY SHIFTED 1σ